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# TENSILE AND INTERLAMINAR PROPERTIES OF GLARE® LAMINATES

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**13. ABSTRACT** *(Maximum 200 words)*
The mechanical properties of several GLARE® laminates were investigated as part of an AKZO-coordinated round robin evaluation program. Tensile, floating roller peel, and three-point bend tests were performed on GLARE® to determine its tensile properties, peel strength, and interlaminar shear strength, respectively. Strength, elongation to failure, and elastic modulus of the GLARE® configurations tested in tension compared favorably to ARALL-4® and monolithic 2024-T3. Peel strength of ARALL-4® was found to be very low in the longitudinal fiber direction due to uninhibited crack front propagation along the fiber/adhesive layer interface. The peel strength of GLARE® was found to be ten times higher than for ARALL® in the longitudinal direction. Three point bend tests revealed an interlaminar shear strength of over 70 MPa.

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# I. INTRODUCTION

GLARE is a family of hybrid laminates consisting of alternating layers of aluminum alloy and fiber/epoxy prepreg. The former can be either 2024-T3 or 7075-T6, depending on which GLARE configuration is used. The prepreg is composed of a 60 vol% loading of R-glass fibers in a thermosetting epoxy resin, which acts as both a binding matrix and an adhesive to the aluminum layers.[1] GLARE was developed by researchers at AKZO and Delft University, both in the Netherlands, and is produced and marketed by AKZO and Alcoa. These organizations have also been responsible for the ongoing development of the ARALL family of aramid fiber reinforced laminates.

ARALL has been limited in its application thus far by, among other factors, its poor compressive properties. The tendency of aramid fibers to suffer microbuckling and premature fatigue failure in compression limits ARALL to tension-dominated applications.[2] GLARE's glass fibers do not suffer from microbuckling, and therefore GLARE is more suitable for applications involving compressive loads. The fatigue resistance of GLARE at R=1/3 is between that of ARALL and 2024, but at R=0 GLARE is vastly superior to ARALL.[1] GLARE also retains the other beneficial properties achieved earlier by ARALL, such as high strength, low density, and good corrosion, impact, and burn-through resistance.[3]

GLARE is currently produced in four configurations, as described in Table I. Each configuration can be produced in a variety of thicknesses, e.g. 2/1, 3/2, and 4/3 ply.[4] The crossply configurations, GLARE-3 and -4, were developed to reduce the anisotropy of the unidirectional configurations, making GLARE-3 and-4 more suitable for applications involving high transverse and shear stresses.

**Table I.**
GLARE Configurations

| Designation | Aluminum | Fiber Orientation |
|---|---|---|
| GLARE-1 | 7075-T6 | Unidirectional* |
| GLARE-2 | 2024-T3 | Unidirectional |
| GLARE-3 | 2024-T3 | 50/50 % Crossply |
| GLARE-4 | 2024-T3 | 70/30 % Crossply |

*- 0.5% post-cure stretch

The purpose of the GLARE evaluation program, in which NADC was a participant, was to evaluate the mechanical and physical properties of GLARE. Test results obtained at NADC are presented here, and are compared to both ARALL-4 and 2024 aluminum sheet.

## II. EXPERIMENTAL PROCEDURES

All GLARE test specimens were supplied by AKZO. The following tests were performed by NADC on the various GLARE configurations:

1. Tensile Tests: The GLARE configurations which were tested are summarized below in Table II. Three specimens of each configuration were tested. Flat, 1/2-inch wide specimens were machined per ASTM B557 by AKZO. Tests were run on an MTS closed-loop servo-hydraulic test machine, operated in load control. Loading rate was 10 MPa/sec (1.45 ksi/sec), with a maximum load of 22.25 kN (5000 lbs). A one-inch MTS extensometer was used for elongation measurement. All load, extensometer, and crosshead

displacement data were recorded by microcomputer at 0.5-second intervals. The yield strength, ultimate tensile strength, and elastic modulus in longitudinal and transverse directions were determined from load and specimen cross-sectional area measurements.

**Table II.**
GLARE Configurations Tested (Tensile)

| Thickness | Type | Orientation |
|---|---|---|
| 2/1 Ply | GLARE-1<br>GLARE-3<br>GLARE-4 | Longitudinal (L)<br>and Transverse (LT)<br>directions (3 each) |
| 3/2 Ply | GLARE-1<br>GLARE-3 | L and LT<br>directions (3 each) |

2. <u>Floating Roller Peel Tests</u>: Peel strength was measured for three prepreg configurations: namely, a single layer of prepreg with unidirectional fibers in the (1) longitudinal and (2) transverse directio~, and also for (3) the adhesive alone without fibers. One-inch wide specimens were prepared per ASTM D3167-76, and as with the tensile tests, three specimens were tested in each of the three configurations. An MTS closed-loop servo-hydraulic test machine was used in stroke control, with a peel rate (stroke rate) of 2mm/sec (4.724 in/min). Load and crosshead displacement were recorded by microcomputer at 0.250-second intervals.

The average peel strength was determined by discarding the first 50mm (1.97 inch) of data and averaging the recorded loads measured over the subsequent 100mm (3.94 inches) and dividing by the specimen width, yielding peel strength values in N/mm (lbs/in). The first 50mm of each test was discarded because in this initial region, the peel mode has not yet stabilized, thus resulting in artificially high load readings. Peel data was also obtained for 5/4 ply ARALL-4, by measuring the force required to peel back the top aluminum layer as in a standard peel test.

3. Three-Point Bend Tests: Three-point bend tests were performed according to ASTM D-790 . The tests were run in stroke control at a crosshead speed of 0.05 in/min. The supports were 10 mm apart and 3 mm in diameter. The specimens were similar to the unidirectional GLARE configurations, but were not representitive of any particular one. They consisted of a 3/2 layup of 2024-T3 aluminum and unidirectional glass-fiber prepreg, with an adhesive film between each of the layers. The specimens were approximately 50mm in length, 10mm in width, and 2mm thick.

## III. RESULTS AND DISCUSSION

Figure 1 shows optical micrographs of (a) GLARE-1 in the transverse direction, showing the unidirectional fibers in cross-section, and (b) GLARE-3, revealing its 0 and 90° plies one on top of the other. In both cases, the adhesive layer between all plies is about 10 $\mu m$, or one fiber diameter thick.

The results of the tests performed are as follows.

1. Tensile Behavior: The results of the tensile tests are summarized in Table III. All values are the average of three tests; standard deviations range from 0 to 5%. The ultimate strengths in the longitudinal direction varied from a low of 696 MPa (101 ksi) for 2/1 GLARE-3 to a high of 1225 MPa (178 ksi) for 3/2 GLARE-1.

The strength levels and anisotropy were consistent with the configuration of the laminates. GLARE-1, the unidirectional configuration, had the greatest longitudinal strength, and the highest anisotropy, as well; the ratio of longitudinal to transverse UTS, $\sigma_L/\sigma_{LT}$, is almost 3 in the 3/2 material. The GLARE-4, with its 70/30% fiber orientation, has a $\sigma_L/\sigma_{LT}$ ratio less than 2, and GLARE-3 with a 50/50 fiber orientation has nearly the same strength in the L and LT directions. The high yield strength of GLARE-1 in the longitudinal direction as compared to GLARE-3 and -4 is due in part to the greater strength of the 7075 aluminum in this material as compared to 2024, and in part to the 0.5% post-cure stretch in this laminate. Stretching imparts a residual compressive stress to the aluminum layers, thus increasing the applied stress at which yielding of these layers occurs.

**Table III.**
GLARE Tensile Behavior

| Specimen Configuration | | Y.S. (MPa) | UTS (MPa) | Elong. (%) | Modulus (GPa) |
|---|---|---|---|---|---|
| 2/1 Ply: | | | | | |
| GLARE-1 | (L) | 689 | 1115 | 3.9 | 67.9 |
| | (LT) | 381 | 457 | 4.6 | 56.5 |
| GLARE-3 | (L) | 327 | 696 | 4.4 | 62.6 |
| | (LT) | 299 | 686 | 4.6 | 62.5 |
| GLARE-4 | (L) | 320 | 1017 | 4.5 | 56.5 |
| | (LT) | 242 | 627 | 4.6 | 50.6 |
| 3/2 Ply: | | | | | |
| GLARE-1 | (L) | 714 | 1225 | 3.9 | 68.0 |
| | (LT) | 352 | 424 | 3.8 | 53.1 |
| GLARE-3 | (L) | 321 | 720 | 4.2 | 59.1 |
| | (LT) | 293 | 753 | 4.7 | 60.0 |

Elongations at failure were generally over 4% in both the longitudinal and transverse directions. The transverse elongation tended to be the higher of the two. Figure 2 shows a typical tensile stress-strain curve for GLARE. Elastic moduli varied from 50 to 68 GPa, depending on configuration, thickness, and fiber orientation in the specimen. These values are somewhat lower than those for 2024, which has a modulus of 72 or 73 GPa.[4,5]

Tensile failure of these laminates involves the release of a large amount of elastic energy by the breaking fibers.[6] This results in severe buckling of the outer aluminum layers in many cases, as shown in Figure 3, as well as almost complete delamination of the material. This delamination occurs at the aluminum/adhesive interface, with about 90% adhesive (i.e. non-cohesive) failure and about 10% fiber/adhesive failure and fiber pullout. Tensile failure is accompanied by partial disintegration of the prepreg layer, which fractures into large fragments upon failure.

Figures 4a and b compare the yield and ultimate tensile strengths of the two 3/2-ply GLARE configurations with those of 3/2 ARALL-4 and monolithic 2024-T3 aluminum. The ARALL specimens were tested at NADC as part of a previous study.[7] It should be noted that the ARALL tests were conducted at a constant strain rate, whereas the GLARE was tested at a constant loading rate. Figure 4c shows the elastic moduli of the same four materials. It can be seen that the unidirectional GLARE-1 possesses higher strength than its ARALL counterpart. This can be attributed primarily to the use of 7075 rather than 2024 in GLARE-1.

2. Roller Peel Behavior: The results of the floating roller peel tests are shown in Table IV. The peel strength of the unidirectional GLARE prepreg is twice as high in the longitudinal direction as it is in the transverse direction. The peel strength of the adhesive without fibers is about 50% greater than the longitudinal strength, although the standard deviation among the three "adhesive only" specimens was very high (around 20%). Figure 5 shows a plot of peel load versus length peeled for a longitudinal specimen.

**Table IV.**
GLARE Peel Strength

| Fiber Orientation | Average Load (kg) | Maximum Load (kg) | Average Strength (N/mm) | ARALL Peel Strength (N/mm) |
|---|---|---|---|---|
| Longitudinal | 19.1 | 22.0 | 7.38 | 0.78 |
| Transverse | 9.34 | 11.0 | 3.61 | 2.44 |
| Adhesive Only | 27.3 | 31.9 | 10.54 | |

Inspection of the peeled GLARE specimens revealed that about 75% of the delamination area was at the fiber/adhesive interfaces, and the remainder was at the adhesive/aluminum primer interface. The high peel strength of all of the GLARE specimens indicates that bonding between the adhesive and the aluminum and fibers is good. This is particularly evident when the GLARE results are compared to the peel strength of ARALL-4 tested at the same peel rate.

The very low longitudinal strength obtained for ARALL results from delamination entirely along the fiber/adhesive interfaces, where the advancing crack front runs undeflected along the interface. The low peel strength in this direction, and the fact that delamination occurred almost exclusively at the fiber/adhesive interfaces, suggest a weakness or brittleness at this interface as compared to the fiber/resin and adhesive/aluminum interfaces. This is supported by results obtained earlier for ARALL-4 in flexural fatigue, which also revealed a strong tendency for delamination along the fiber/adhesive interfaces.[8] In the transverse direction, the advancing crack front is deflected each time a fiber is encountered, resulting in a much higher peel strength. The peel strength values obtained for ARALL are in excellent agreement with those reported by Alcoa.[9]

GLARE does not show any such interfacial weakness in the longitudinal direction, as revealed by the higher longitudinal peel strength and mixed failure mode. The fiber/adhesive delamination in peel tests contrasts sharply with the 90% aluminum/adhesive failure in tension. The difference in delamination crack path between tensile and peel failure, as well as the mixed failure mode in peel, is facilitated by the relatively low ratio of fiber/adhesive peel strength to aluminum/adhesive strength (about 0.7), as reported in Table IV. The delamination behavior in tensile failure is probably also affected by the near-impact nature of the shear loading encountered when fiber failure occurs.

3. Three-Point Bend Tests: The bend tests performed on the GLARE specimens as supplied by AKZO (10 mm wide by 50 mm long) indicate an interlaminar shear strength (ILSS) of 75.6 MPa. These specimens were much longer than those specified by ASTM D-790 (14.2 mm), and as a result, complete interlaminar fracture did not occur. Delamination occurred in about a 10 mm region, starting at the mandril and extending over one of the

supports. The delamination was accommodated by two opposing bends in the specimen, i.e. an upward bend at the mandril and a downward bend at one support.

Bend tests were also performed on specimens conforming to the dimensions specified by ASTM D-790. These, as was expected, demonstrated a slightly lower ILSS than the longer specimens. Shear strength in these specimens was about 71 MPa.

## IV. CONCLUSIONS

1. The tensile strength and elastic modulus of the GLARE configurations tested are comparable to those of ARALL-4 and 2024-T3.

2. The peel strength of GLARE is about ten times higher than that of ARALL-4 in the longitudinal direction, and about 50% higher in the transverse direction.

3. The peel strength of ARALL-4 in the longitudinal direction is very low due to undeflected crack front propagation along the fiber/resin interfaces within the fiber layer.

4. The interlaminar shear strength of GLARE in three-point bend tests is about 71 MPa.

## V. REFERENCES


1- J.W. Gunnink, "Aerospace ARALL- The Advancement in Aircraft Materials", in Proceedings of the 35th International SAMPE Symposium, Vol.35, No.2, 1990.

2- P.R. Langston, "Design and Use of Kevlar in Aircraft Structures", SAE General Aviation Meeting and Exposition, 1985.

3- J.W. Gunnink, "Aerospace ARALL- A Challenge for the Aircraft Designer", in Proceedings of the 36th International SAMPE Symposium, Vol.36, No.2, 1991.

4- AKZO Advertisement, "Aerospace ARALL: GLARE"

5- Metals Handbook, 8th Ed., Ed. T. Lyman et al, Vol.1.

6- G. Roebroeks, Private Communication.

7- M.E. Donnellan and J. Cook, "Evaluation of ARALL-4, an Aramid Fiber Reinforced Aluminum Laminate", NADC Report No. NADC-89100-60, Oct. 1989.

8- J. Cook and M.E. Donnellan, "Flexural Fatigue Behavior of ARALL Laminates", NADC Report No. NADC-90073-60, August 1990.

9- R. Bucci, Private Communication.

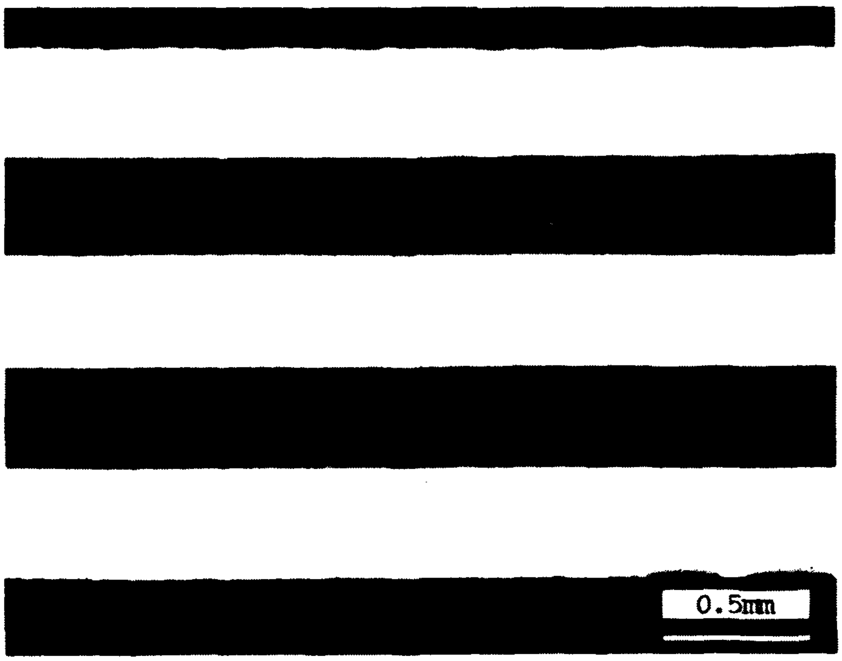



Figure 1a. Optical Micrograph of GLARE-1 (Transverse Direction). Fibers are Unidirectional at 0°.

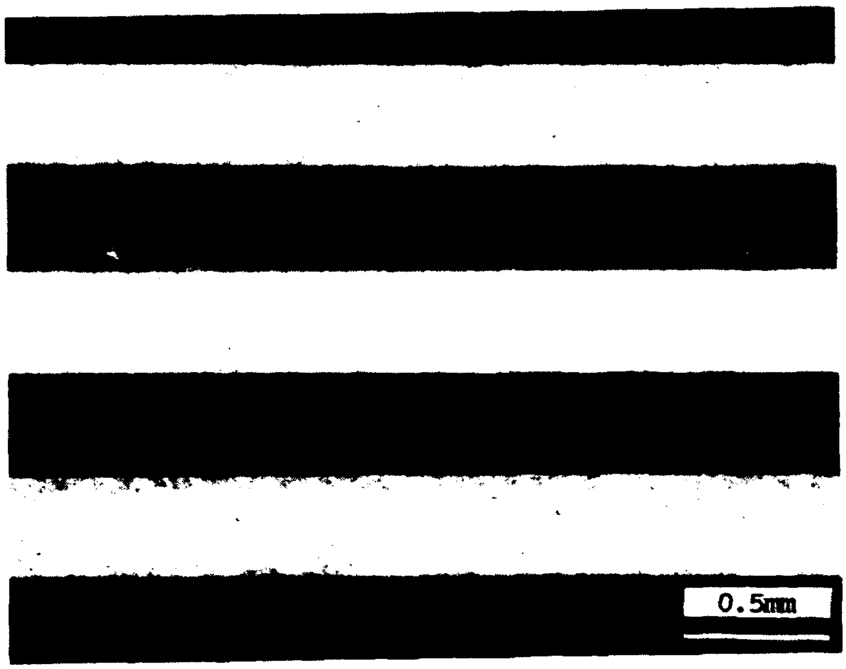



Figure 1b. Optical Micrograph of GLARE-3 (Transverse Direction). Fibers are Oriented at 0° and 90°.

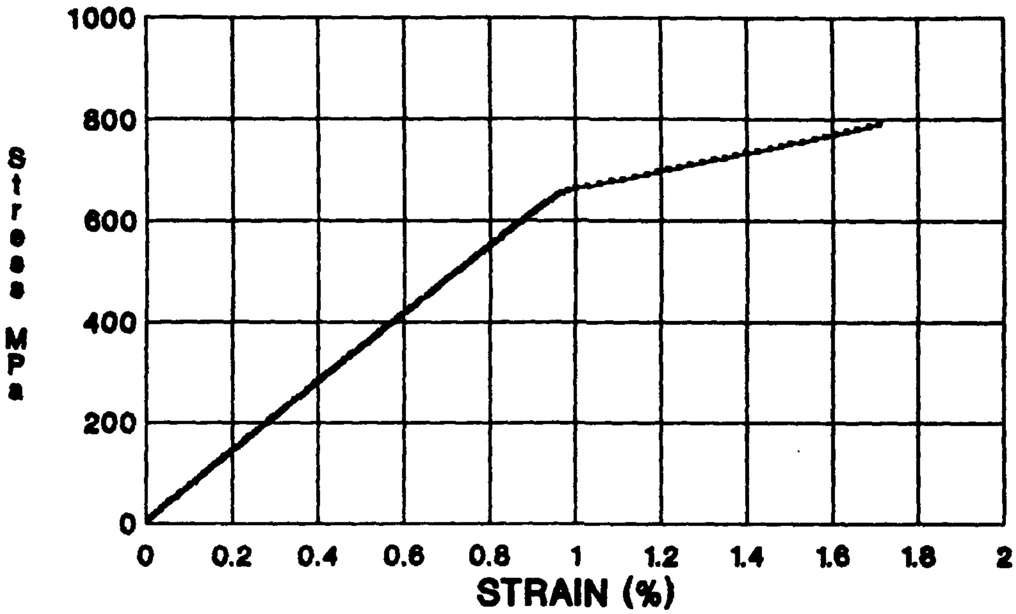
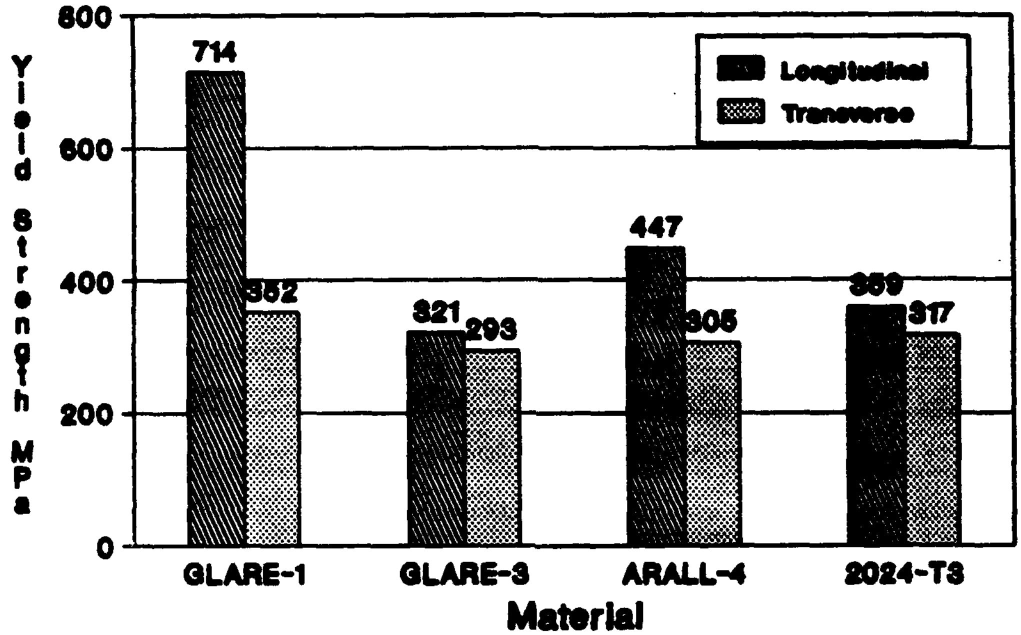



Figure 2. Partial Stress-Strain Curve for Longitudinal GLARE-1. Final Fracture Occurred at 1136 MPa and 4.1% Elongation. The Change in Modulus Denotes the Onset of Yielding in the Aluminum Layers.

Figure 3. A Failed Tensile Specimen (Longitudinal GLARE-4). Extensive Damage was a Result of the Large Amount of Elastic Energy Released upon Fiber Fracture.



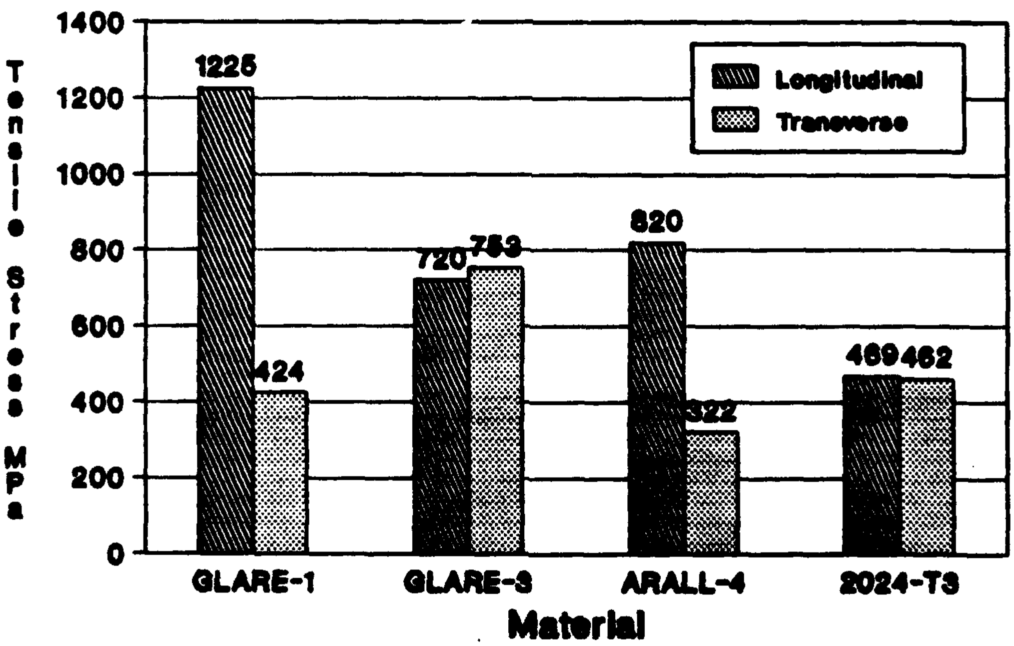




Figure 4. Tensile Strength of 3/2 Ply GLARE-1 and -3 Compared to 3/2 ARALL-4 and 2024.
(a) Yield Strength. (b) Ultimate Tensile Strength.

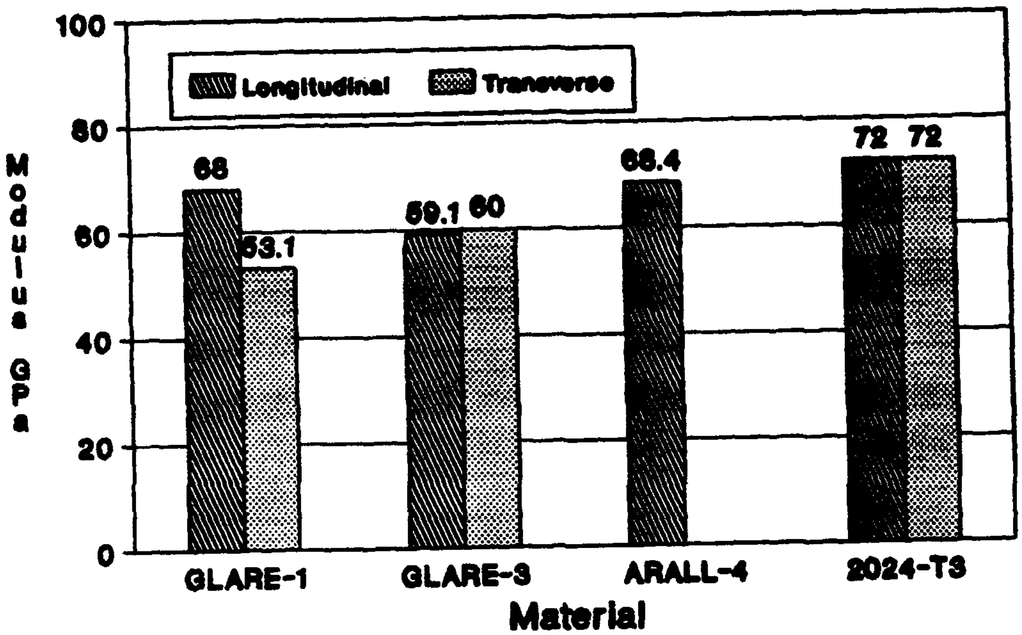



Figure 4(c). Tensile Modulus of GLARE versus ARALL-4 and 2024.

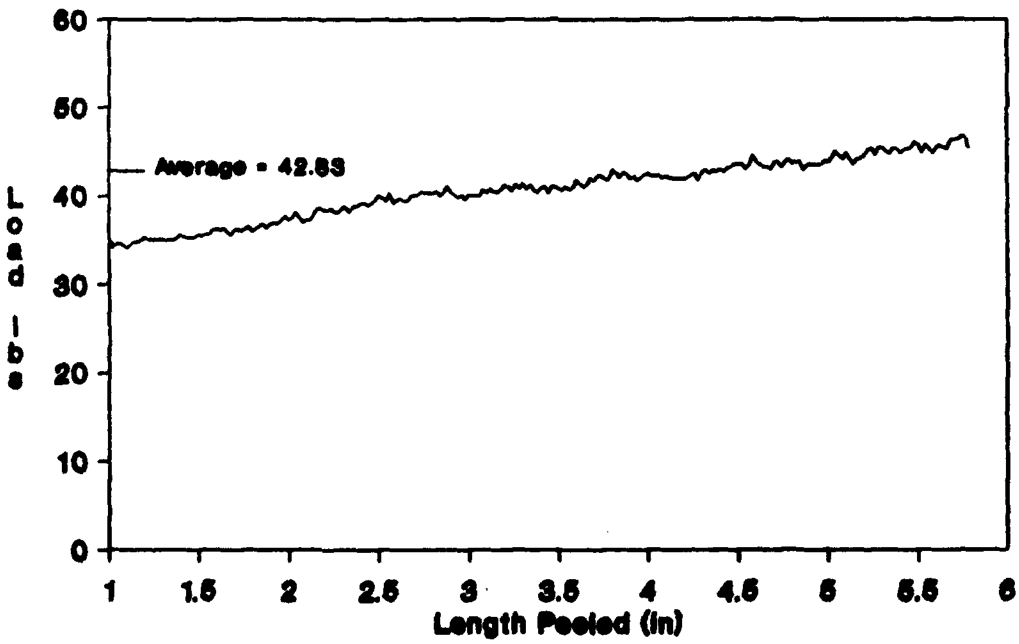



Figure 5. Plot of Peel Load versus Length Peeled for Longitudinal GLARE.

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